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PRACTICAL APPLICATIONS OF BASIC RESEARCH ON IMPULSE NOISE HAZARD

G. Richard Price

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To assess impulse noise hazard accurately, procedures should be based on the physiological mechanisms underlying hearing loss. Information from basic research studies is relevant in three areas. First, there is a spectrally dependent "critical level" above which loss mechanisms change from a mode that is probably metabolically based to one that is mechanically based. Stimulation at and above this second mode should be avoided. Second, in spite of the regulatory trend ignoring the time

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pattern of stimulation, studies continue to indicate that intermittency ameliorates the effect of noise, producing less effect for a given amount of energy in the exposure. Lastly, a variety of sources can be interpreted as indicating that meters designed to rate hazard should have: a rise-time capability in the vicinity of 20 microseconds; a dynamic range of over 100 dB; and employ a frequency weighting function such as A-weighting, although the shape is not critical due to the relatively sharp tuning of the ear and the generally flat noise spectra commonly encountered in the work place.

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APPROVED: John D. Weisz
JOHN D. WEISZ
Director
US Army Human Engineering Laboratory

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US ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland 21005-5001

PRACTICAL APPLICATIONS OF BASIC RESEARCH ON IMPULSE NOISE HAZARD

Most of us have the strong feeling that we know impulse noise when we hear it; yet when we try to develop an unambiguous definition of an impulse, we quickly discover that we need a way to separate the arbitrary from the essential. For example, how long must a burst of sound be before it is properly considered intermittent continuous sound rather than an impulse? Or how much above the background intensity must a burst be before it is considered an impulse? This paper focuses on impulse noise as a hazard to hearing; therefore the touchstone used to separate the arbitrary from the essential is the physiological response of the ear itself. The structure of the ear and its response to sound are essentially fixed (even though our knowledge of them is still incomplete). However, given even our present understanding, it is possible to develop a number of practical ideas for the measurement and rating of impulse noise hazard.

Basic research findings can be related to practical impulse noise issues in three areas. The first is the question of whether there is a change in the mechanism of loss as the intensity of stimulation rises, i.e. is there a "critical level"? (Price, 1981). If there is, then more than one method of rating loss will be necessary, depending on the intensity of the sound. The second question is whether the time pattern of sound presentation influences the amount of loss (does intermittency matter?). If it does, then simple integration of energy as proposed in ISO/DIS-1999 (1984) will prove to be a less useful method of rating impulse noise hazard. Lastly, there is a constellation of issues surrounding measurement systems, e.g. rise time capabilities, band-width requirements, dynamic range, frequency weighting.

IS THERE A CRITICAL LEVEL?

Behavioral data from humans (Ward, Selters, and Glorig, 1961), electrophysiological data from cat (Price, 1968) and histological data from guinea pig (Spoendlin, 1976) and chinchilla (Ward, 1983) have been interpreted as showing that there is a frequency dependent level at which loss processes within the ear change to an essentially mechanical form (Price, 1981; 1983). If this is true, it follows that losses above this level, insofar as they are more like a bruise or tear of the sensory cells rather than metabolic fatigue, may take an extended time to recover, and should probably be avoided because of the likelihood of permanent loss. An estimate of this level has been calculated for the 50th percentile human ear and appears in Fig. 1. Fig. 1 indicates that

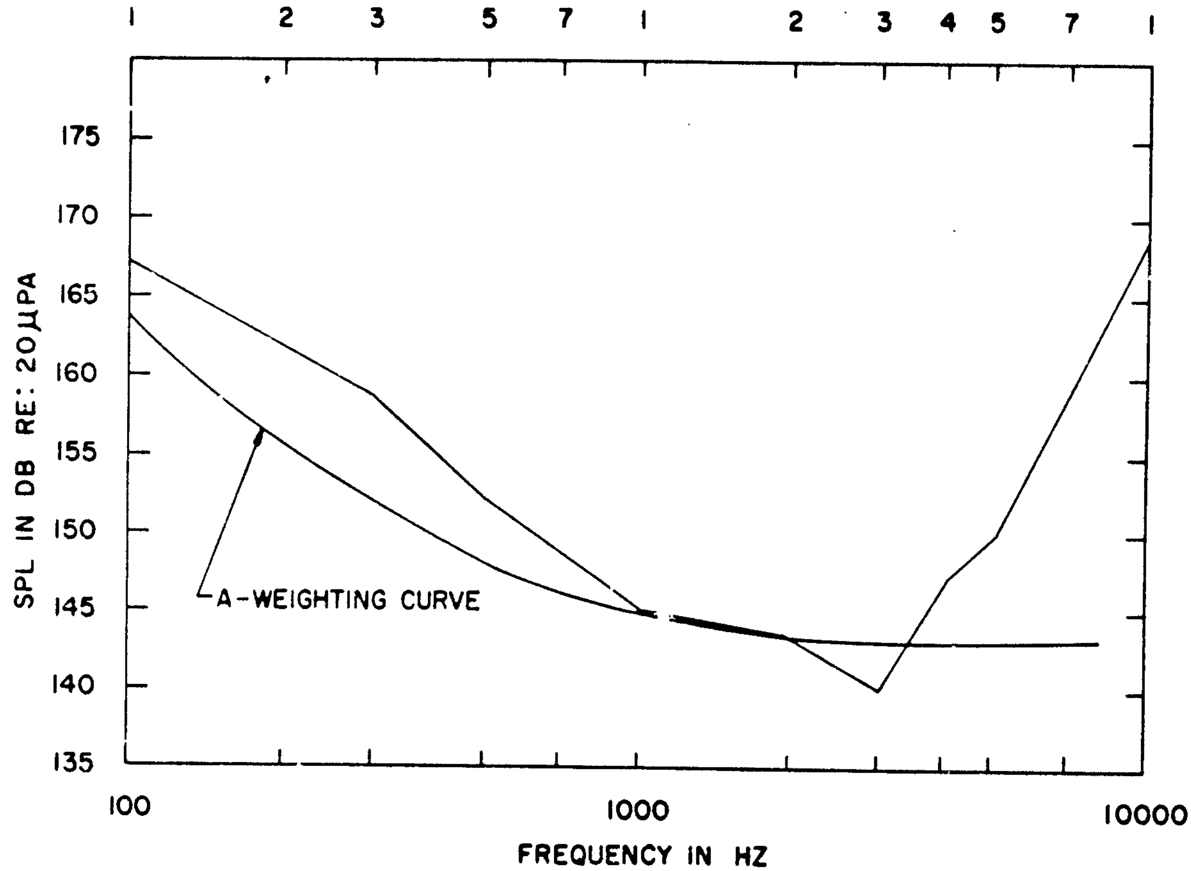

Fig. 1. Calculation of a critical level for the median human ear for a damped sinusoid arriving at normal incidence. The A-weighting curve is shown for comparison. From Price (1981).

the ear should be most susceptible to frequencies in the mid-range, and that when peak levels rise to the vicinity of 140 dB, half of the population may be at risk. Some impulses in industrial settings are in this region and may partially explain the unexpectedly large losses seen in some ears. Some recent data on permanent hearing losses resulting from brief pulses of sound from cordless telephones (Singleton, Whitaker, Keim, and Kemker, 1984) are also consistent with this contention. Where noise standards are concerned, the likely presence of a critical level implies that there should be an upper limit to exposures in this vicinity as ISO/DIS-1999, and the proposed ANSI S3.28 standard methods for evaluating the effect of intense sound prescribe. It might be noted in passing that almost all fire-arm noise exposures are above these levels; therefore only protected exposures should be allowed.

DOES INTERMITTENCY MATTER?

By definition, impulse noises have intermittency as their essential character; therefore this question is central to the issue of whether impulse noises somehow represent a special hazard. The regulatory Zeitgeist seems to strongly favor the position that intermittency does not matter. Insofar as the recommendations of ISO/DIS-1999 are taken to be representative, then only the total energy (A-weighted) is needed to predict the permanent loss resulting from daily exposure to noise. This argument has clearly gained ascendency; however, the evidence in favor of this position is extremely weak. For example, for a given amount of energy input indicative of working a number of years in noise, the range of

threshold shift resulting is commonly 60 or 70 dB (Burns and Robinson, 1970) and the standard deviation of permanent threshold shifts exceeds 20 dB (Sulkowski and Lipowczan, 1982). Or, looked at in another way, the correlation between permanent threshold shifts (PTS) and immission is on the order of 0.2 for both continuous and intermittent noises (Burns and Robinson, 1970). This low correlation implies that only about 4% of the variance is being explained by the immission concept; but the method survives largely because it is easily instrumented, easily applied, and no clearly superior alternative is currently available.

In seeking an alternative, it is reasonable to suppose that much of the variability is a function of individual differences in susceptibility (Price, 1984a). Such differences may simply be something that has to be lived with (at least until some test of susceptibility is devised). But in addition, two factors, acting in opposite directions, can be adduced to explain the extreme range of variability. Studies done in the laboratory generally show that intermittency acts to reduce the effect of a given amount of energy (Ward, 1984; Ward, 1973). Actions of the middle ear muscles and a variety of homeostatic mechanisms have been called upon to explain the beneficial effects. Therefore, the ameliorative effects of intermittency may be why some individuals lost much less sensitivity than would have been predicted. In the past, the laboratory studies of intermittent stimulation were persuasive enough that trading ratios of 4 or 5dB per halving of exposure time were incorporated into the standards then being developed (U.S. Air Force, 1973; CHABA, 1964).

Acting in the opposite direction, it is possible that the measurement techniques used may have under-represented the full noise exposure. Per Brüel (1977) has argued that because of the time constants built into most measuring devices, intense transient stimuli are not measured accurately. For example, a Friedlander impulse, with an A-duration of 90 microseconds, would have its peak energy where the ear would be predicted to be most susceptible (Fig. 1). The peak level measured by a sound level meter set on "impulse" would be more than 30 dB lower than the true peak (Price, 1984b). Brüel has shown that essentially the same error would apply to a measurement of the noise of a pneumatic nailing machine and to a lesser extent to a variety of noise stimuli (Brüel, 1977). Measurement errors may thus be very large and may explain why Passchier-Vermeer's analysis of hearing loss in noise-exposed people (1971) showed that an allowance of 13 to 20 dB should be made for additional hazard for impulsive noises. In addition, it is possible that intense transients may have often been excluded from routine noise measurements because they were not held to be typical of a particular environment. Thus, for a variety of reasons, the true exposure may have been understated, and ears so exposed would have more threshold shift than expected. Furthermore, if there is in fact a critical level, more intense stimuli may have disproportionately large effects (Price, 1981).

The practical implication of these arguments is that there may be alternate approaches to reducing noise hazard. If the logic implicit in ISO/DIS-1999 is followed, the answer is to reduce the energy. Reducing the energy is probably not a bad idea; however in practice it may not be technically or economically feasible to effect a significant reduction of total energy. On the other hand, it is possible that there may be situations in which significant improvements could be achieved by tailoring the timing of the exposure to permit recovery processes to begin (Price, 1976, 1974a) or by reducing the noise during the "off" period, thereby allowing recovery from the more intense portions of the exposure (Klosterkötter, 1970). If these factors were incorporated into a noise standard it would doubtless be much more complex than ISO/DIS-1999; however microprocessor technology promises to make even complex paradigms useable.

IMPLICATIONS FOR MEASUREMENT DEVICES

Onset Time Constant The mechanisms responsible for hearing loss operate essentially at the periphery. This means that meters intended to rate hazard should account for the energy actually entering the cochlea. Work with a model ear and impulses has shown that the acoustics of the external ear degrade the rise of even a shock wave to 20-30 microseconds at the ear drum position (Price, 1974b). Further, the mass of the ossicles establishes a high frequency cutoff above the resonance frequency of the ear. If one accepts the highest frequency of interest as 10 kHz, then a system that can reproduce rises of 20 microseconds should be adequate for describing hazard. The much longer time constants built into current meters are essentially the result of an attempt to reproduce the perceived loudness of sounds, which includes processing by the central nervous system.

Dynamic Range One of the great challenges for the designer of the ultimate instrument will certainly be the extreme range of intensities important to the normal ear. At the low end, noise standards commonly have a threshold in the 85 dB region, based on the idea that work day exposures at this level will produce no significant hearing loss. However, as alluded to earlier, noise levels low enough to interfere with recovery (less than 60 dBA) can affect the amount of TTS in response to more intense exposures (Schmidek, Margolis, and Henderson, 1975). At the high intensity end, the possible existence of a critical level in the vicinity of 140 dB argue that at least this level must be within the capacity of an instrument; but that some different system of rating hazard will be needed if rifles at 160 dB and cannons at 180+ dB are to be included. If the foregoing perceptions are accurate, an ultimate instrument to be used in industrial settings will need a dynamic range in the vicinity of 100 dB!

Frequency Weighting The use of A-weighting for rating hazard has gained general acceptance, although it is not clear why a weighting curve that was originally intended to parallel the loudness of moderately intense sounds should do well at rating the hazard at high intensities. Price (1982) examined the use of A-weighting and in essence argued as follows. As sound is conducted toward the inner ear, the obstacle effect of the head and the resonance of the external ear combine to emphasize sounds in the mid-range (Wiener and Ross, 1946). The stiffness of the middle ear discriminates against the low frequencies and its mass cuts off the high frequencies. Therefore, the sound entering the cochlea is effectively band-pass filtered. The mechanism responsible for loss within the cochlea is probably metabolically based at low intensities and mechanically based at higher intensities; but it in any case, is likely that whatever the mechanism, its change with frequency will be relatively slight compared to the tuning of the external and middle ears. The result, one form of which is expressed in Fig. 1, is that the tuning of the ear is relatively sharp and not too different than A-weighting. On the other hand, Burns and Robinson (1970) found that the spectrum of workplace noises is relatively flat (extreme slopes of +- 6 dB/oct). The net result is that the ear is more sharply tuned than the noise, and sounds in the mid-range are conducted into the cochlea best. This analysis is consistent with the common observation that noise induced hearing loss almost always is greatest in the mid-range, regardless of the noise exposure. We can therefore conclude that although A-weighting might not be an exact match for the loss function of the ear; some frequency weighting is necessary. Given the broad spectral tuning of most noises, A-weighting is located at essentially the right frequency and its cutoffs are sharp enough to do the job. This conclusion is essentially borne out by Robinson's (1983) reanalysis of hearing levels and noise in industry in which he concludes that with respect to the choice of A-, B-, or C- weighting, the choice is not critical.

CONCLUDING COMMENT

The foregoing analysis has essentially argued that the hazard from impulse noise is physiologically complex, involving a wide dynamic range, a wide band-width, a spectrally dependent critical level at high intensities and an interaction between loss andrecovery processes during intermittent stimulation. The present trend toward the use of an A-weighted energy measure is almost certainly too simple to be accurate in individual cases; however nothing better is in the immediate offing. In looking to the more distant future, there is hope that with a better understanding of how the ear works and improvements in microprocessor technology, it may eventually be possible to implement a paradigm like that proposed by Botsford (1971) that will be effective in dealing with the full complexity of the auditory system's response to noise.

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